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FEASIBILITY OF INTERACTIVE DATA PROCESSING IN A SEISMIC SURVEILLANCE SYSTEM

Robert L. Sax

Texas Instruments, Incorporated

Prepared for:

Advanced Research Projects Agency
Air Force Technical Applications Center

31 December 1974

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FEASIBILITY OF INTERACTIVE DATA PROCESSING IN A SEISMIC SURVEILLANCE SYSTEM

TECHNICAL REPORT NO. 12

VELA NETWORK EVALUATION AND AUTOMATIC PROCESSING RESEARCH

Prepared by
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ABSTRACT

An interactive data processing system enables a seismic data analyst to interrupt and modify the automatic processing of seismic data. It results in increased efficiency of retrieving desired seismic data. Also, it results in increased capability of the analyst to accurately describe and document seismic events.

Principles are described to effectively design software for a seismic interactive data processing system. A set of tasks were described in detail as promising applications. Certain functions needed for seismic surveillance will require a very effective interactive data processing system.

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SECTION I
INTRODUCTION

The definition of an interactive processing system is that which enables an analyst to efficiently interrupt and modify computer processing. This is done by observing the results of processing and by inputing additional information to influence the results of future processing. In this report, a number of options will be described for appropriately using interactive processing to execute selected tasks needed for effective seismic surveillance.

The hypothetical seismic surveillance system under consideration consists of a network of about 25 seismic observatory stations located around the world. It is assumed that each station will collect data from arrays of long-period and short-period seismic sensors and will have the capability to automatically process that data. Also, each station will be connected with communication links over which the data can be sent. By means of this communication capacity, the remote stations will deliver seismic data to a central facility serving as the surveillance system headquarters.

The delivery of seismic data from remote stations to the central facility can either be done selectively, by utilizing low rate communications and on-site data processing at each station, or by sending all of the raw seismic data and doing all of the data reduction at the central facility. In either case, substantially the same processing functions are needed to reduce the data to significant event information. Therefore, the following analysis of interactive processing is relevant to either mode of data collection. In the following, it is assumed that data is sent selectively from remote stations to the central facility. For the case of a centralized data processing system, merely consider that the station processors and storage elements exist in the central

facility and are linked to the other central facility processing functions by data channels into a common storage element. The costs, tradeoffs, and design problems associated with either approach were described in an earlier report by Texas Instruments Incorporated (1974).

The following functions are performed on raw seismic data collected at remote stations:

- Collect and hold raw sensor data for a specified length of time.
- Automatically generate bulletins to indicate possible seismic events.
- Forward those detection bulletins from all of the stations to a processor which makes preliminary event locations.
- Reduce each stations raw seismic sensor data to waveform estimates of each event.
- Temporarily retain backup files of the raw seismic data.

The following functions must be performed at the central facility:

- Make a preliminary location of events using the information on station detection bulletins.
- Request waveforms from stations at computed arrival times of possible events.
- Classify those events of special interest. These require recording of all of the array sensors at selected stations and in some cases by records of extended duration.
- Request the seismic data needed to document classified events of special interest.

- Monitor and control the quality of all processes carried out to detect, describe, and classify the seismic events.
- Deposit sets of selected event phases into a data bank and withdraw needed data from the data bank.

To implement the data processing required for the above functions, choices must be made between using 1) an automated processing system, 2) an interactive processing system or 3) a batch processing system. Some combination of all three of these data processing modes should result in maximum efficiency in executing given functions. The degree to which an interactive processing system is needed to accomplish a function depends on the efficiency of data processing and on realizing significant benefits from human interpretation. These choices in designing the data processing system should be considered at all of the major decision points in the analysis sequence which influence the data flow from remote sensors to the data bank. The cost of interactive processing must be justified by the designers evaluation of gains in the efficiency and the capability to detect events. These are the main factors affecting the choice of a data processing system to implement the functions required for seismic surveillance. To improve computational efficiency, interactive processing must effectively trade off the general purpose computer's complexity required to compile any conceivable program for the special purpose computers prompt execution of interpreter driven pre-stored program modules. To improve the capability of detecting events, the human analyst must intervene effectively between machine processing steps to beneficially influence the selection of desired data and thereby affect the data flow from one place to another.

The following section will discuss the design requirements for interactive processors. This will be followed by an outline of the organization of seismic surveillance system by command levels to facilitate the analysis of

interactive processing. Finally, some special analyst invoked procedures will be discussed, which provide possibly promising applications of interactive processing.

SECTION II

GENERAL REQUIREMENTS FOR DESIGNING INTERACTIVE PROCESSORS

In the previous section, it was pointed out that an interactive data processing system can sometimes provide an analyst with the best means of carrying out his tasks. By using an interactive system, the analyst can invoke displays of data. This data enables him to interpret and modify the routine automatic processing for which he is responsible. As a result of what he sees, he may intervene in the data processing by means of a keyboard or by other means of inputting data or control information. Some tasks, for which the analyst is responsible, are executed more efficiently and more accurately, by including visual interpretation of data, than by any known automatic processing algorithm. Some examples are: 1) the timing of the start time of a P wave, 2) selecting a set of stations with the most reliably timed P waves, 3) alignment of event waveforms with low S/N ratio, 4) determining which dispersion curve is most consistent with an ambiguous set of long-period group velocity measurements. Probably, the most promising application for interactive processing are those in which the analyst is dedicated to a well defined function fulfilled by a diverse set of programmed tasks; especially those which benefit by the analyst's interpretation of seismic waveforms or by interpreting otherwise ambiguous plots of seismic measurements.

The seismic surveillance problem will necessitate implementing a set of functions which must be carried out to detect and describe seismic events. For example, each seismic event should be described by

event location, origin time, magnitude, and other parameters. Events should be further documented with time traces of selected event phases which are obtained from a selected set of station measurements. To achieve all of this, the function processes control data reduction and data flow from the time and place of sensor measurements until the documented event is deposited into a seismic data bank. In Figure II-1 and Table II-1, a set of such functions is shown. These are shown to control the data reduction and data flow and also to monitor the status of the station processors. In executing these functions, the application of interactive processing is obviously needed for the event classification processor (ECP); and optionally for some of the other processors.

A useful role can be played by interactive graphics in a seismic surveillance system. That role is to interface each seismic analyst with the machine processing needed to perform his function. This enables the analysts to intervene for the purpose of 1) monitoring inputs and outputs, 2) evaluating and reporting his workload and processing results, 3) executing optional computations, 4) correcting errors, and 5) altering priorities, protocol, thresholds, and algorithms as instructed by the system control processor (SCP).

The following capabilities will be needed to efficiently carry out the preceding list of purposes of interactive processing. These will enable the analyst to utilize the full potential of hardware and software dedicated to the function for which he is responsible.

- Invoke programs as sub-tasks in any preconfigured sequence
- Modify tasks by adding or deleting sub-tasks
- Optionally interrupt a sub-task to repeat a computation or to change a program parameter
- Create new tasks by combining old tasks

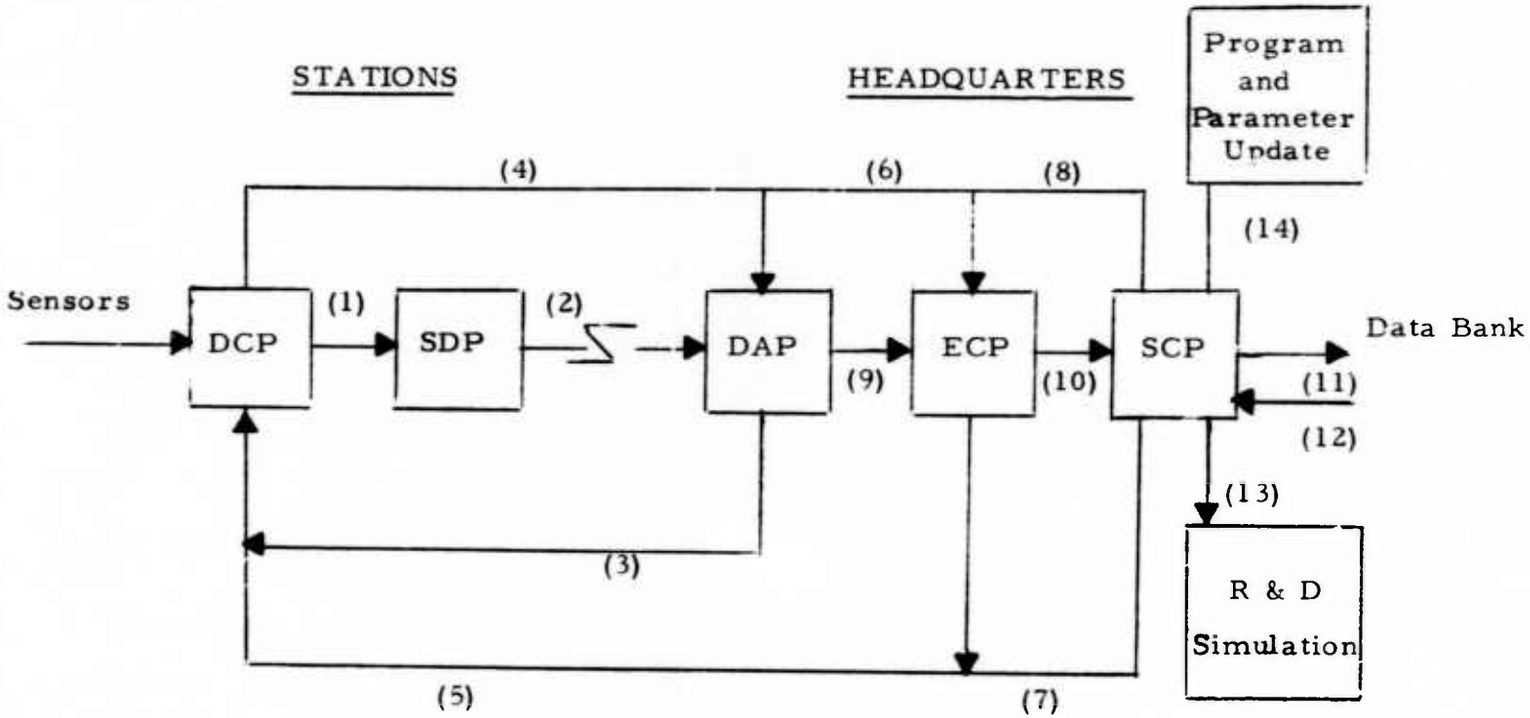


FIGURE II-1

SYSTEM FORWARD AND FEEDBACK OF DATA AND INFORMATION

TABLE II-1

SYSTEM FORWARD AND FEEDBACK OF DATA AND INFORMATION

FUNCTIONS	
DCP	Data Collection Process
SDP	Station Detection Process
DAP	Detection Association Process
ECP	Event Classification Process
SCP	System Control Process

ACTIVITIES	
(1)	Buffer time gate of raw data
(2)	Beam and send detection, bulletins to headquarters
(3)	Request waveforms or additional detection information
(4)	Return waveforms or additional detection information
(5)	Request all sensors for extended processing
(6)	Return all sensors for extended processing
(7)	Request calibration, station equipment or operating status, or update station parameters or programs
(8)	Return station equipment or operating status, calibration, experimental data
(9)	DAP report
(10)	ECP report
(11)	Update data history
(12)	Retrieve data bases
(13)	R&D, eval on data bases
(14)	Data for program testing and program parameter update

- Edit programs
- Rapidly recover from analyst error
- Log all computation and invoked instructions.

For interactive seismic processing, a special purpose command language can be used to accomplish the above capabilities. A system utilizing such a language is shown on Figure II-2. This system, designated as a seismic analyst's problem solving system (SAPSS), is modeled after the numerical analysis problem solving system (NAPSS) of Roman (1973).

This seismic command language is composed of the following software modules:

- General supervisor
- Command supervisor
- Interpreter supervisor
- Console support routines
- Command processors
- Processing modules.

The work flow diagram on Figure II-3 shows that the control is partitioned between supervisors and describes their resultant actions. In summary, the general supervisor prompts the user for input. By detecting a response, the general supervisor invokes the command supervisor to test the command for validity. If valid, an interpretation code is given to the general supervisor. It then passes control to the interpreter supervisor. The interpreter supervisor executes the sequence of command processors which control the processing modules. Both the command processors and processing modules are in executable form and are invoked without compilation.

SAPSS SYSTEM

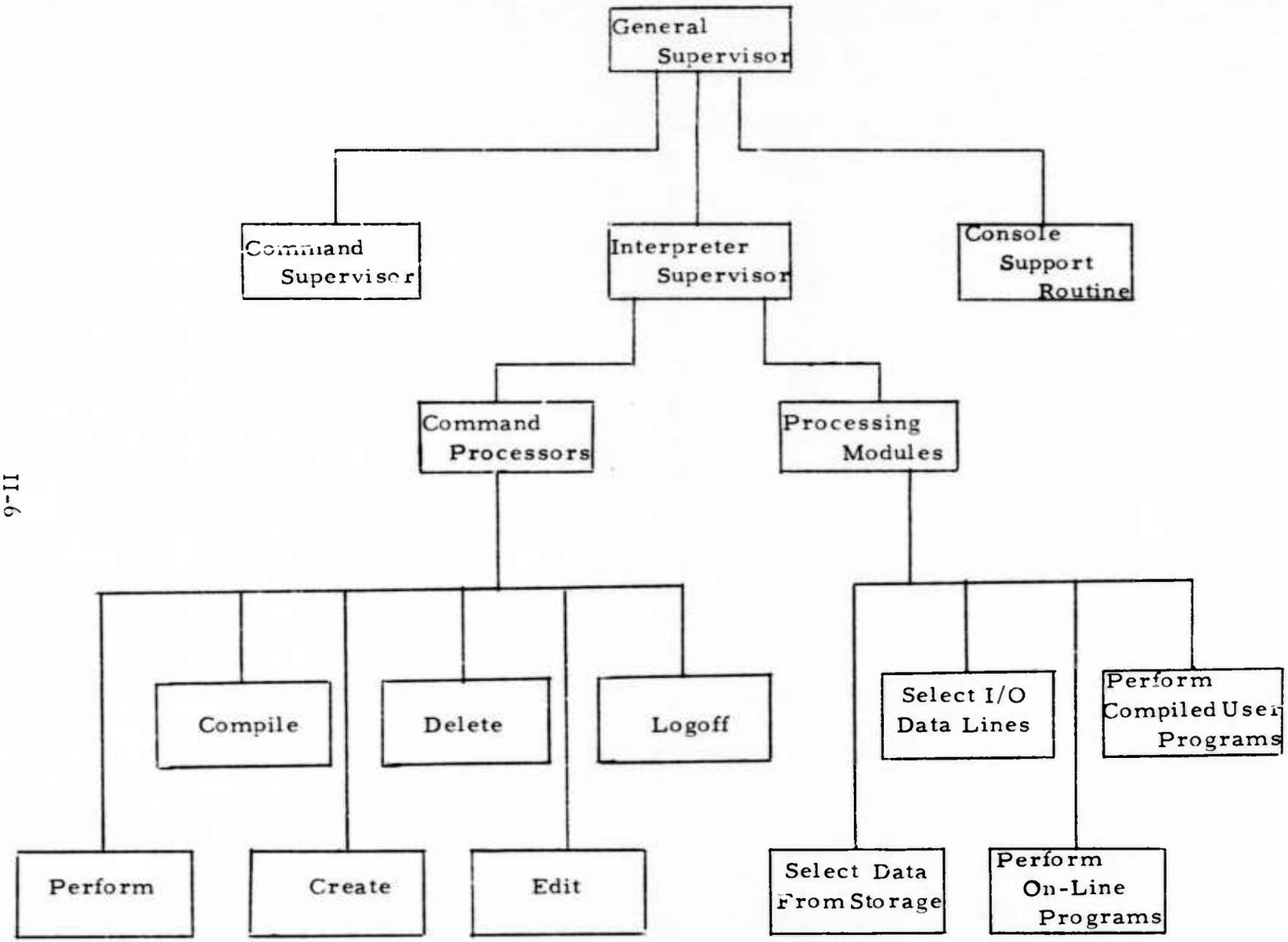
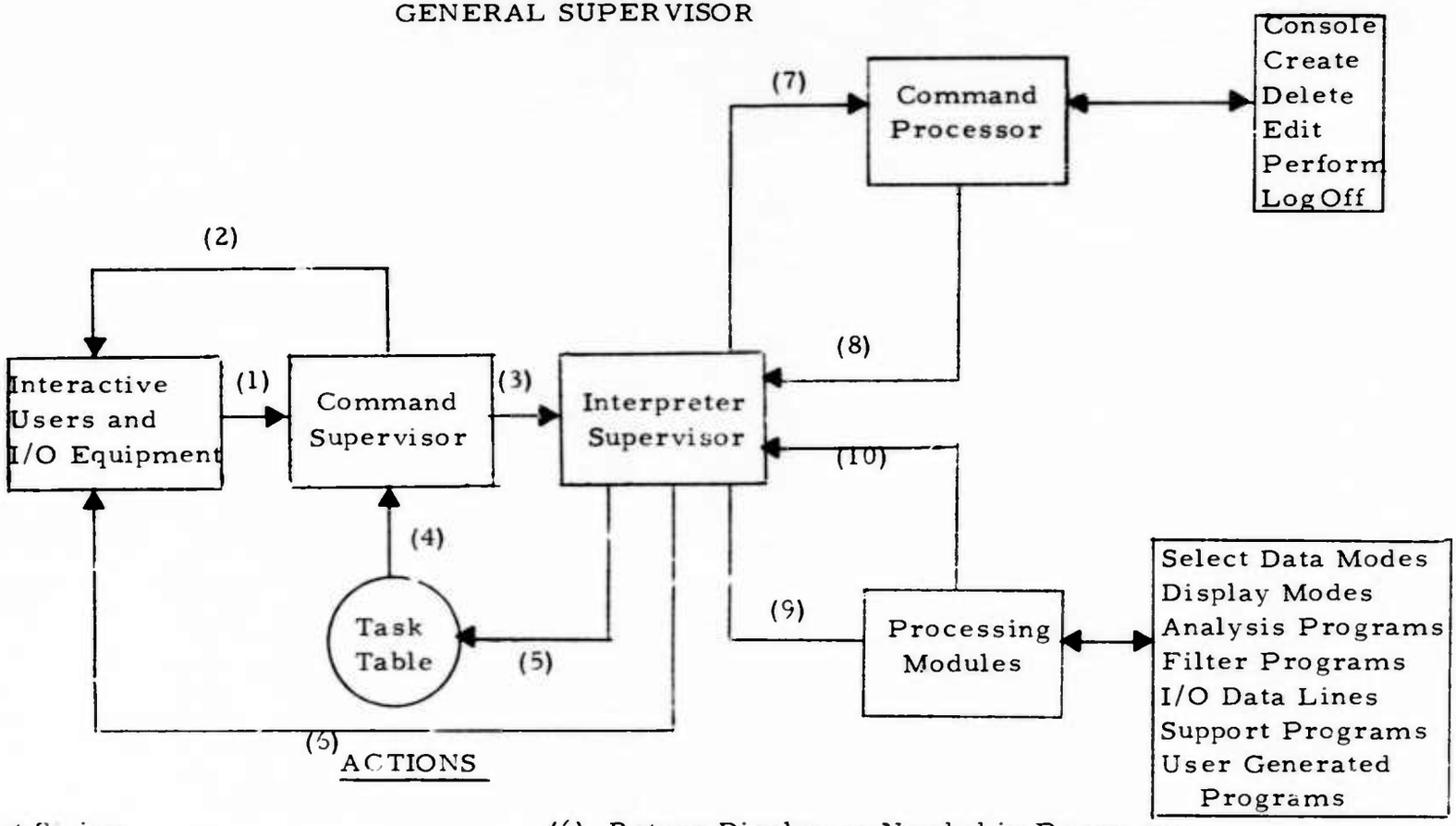


FIGURE II-2
SYSTEM STRUCTURE

SAPSS SYSTEM

GENERAL SUPERVISOR



(1) Input String
(2) Error Messages and User Prompting
(3) Pass Interpretation Code
(4) Retrieve Task
(5) User Modification of Task Table
(6) Return Display as Needed in Programs
(7) Retrieve Command Program
(8) Execute Command Program
(9) Retrieve Processing Program
(10) Execute Processing Program

FIGURE II-3

WORK FLOW

Further provision is made to compile very simple user programs. These programs can be executed directly by appropriately expanding the command language. This is accomplished by altering the task table interpreter code by a sequence of instructions. Such specially compiled programs provide a capability to make rapid numerical calculations using the results of jobs run with the standard process modules and provide I/O control of these results. Under these design guidelines, there is no need for compilers, which require machine language coding. The purpose of this capability is to provide a fast and flexible means to summarize the results obtained by standard process modules and to present these results in a variety of output formats.

SECTION III

COMMAND LEVEL ORGANIZATION OF THE DATA PROCESSING

A. INTRODUCTION

The data processing system required for seismic surveillance is organized by a set of command levels. At a command level, an analyst or computer operator is responsible for some aspects of event detection, measurement, classification, and data processing quality control. Also, at a command level, certain capabilities to process the seismic data are available to the analyst. The extent of these capabilities will depend on the type of data or information available and on the geographical diversity of the data. For example, at a seismic station, a large amplitude measurement may be interpreted as a possible seismic event. As a result, a bulletin describing the possible event is generated and sent to the central facility. The main information conveyed by this station detection bulletin is an estimate of the arrival time of the event P wave. Other information includes the direction, velocity and the amplitude of the wave. All of the detection bulletins received from remote seismic stations are processed at the central facility. After waiting long enough to receive almost all of the bulletins assocated with a possible event, the detection assocation processor (DAP) operates on the accumulated stack of detection bulletins. The DAP automatically selects a sub-set of bulletins which it assocates to estimate an event location. The DAP then orders waveforms to be sent from a number of stations in order to document the event. Success in retrieving event waveforms depends on

the accuracy of the estimates of focus location and origin time since these measurements are needed to compute the arrival time of the event at those stations where the event is not readily discernable.

The example demonstrates the significance of geographical diversity of data to the problem of data reduction. Bulletins from around the world enable the DAP to locate the event. The feedback of computed arrival times and ray parameters to the seismic stations enable automatic station processors to beam the event and send back waveforms. Assume 2 minute time windows for P waveforms, arrays consisting of 20 sensors, 25 events per day, and assume that there are no false waveform requests; this points to a potential data reduction of the order of 500:1. Besides obviously cutting the cost of communications, DAP feedback also cuts the cost of data processing. The data processing of event waveforms at the central facility is simplified by this reduction of data. In a centralized system, the cost of data processing is also reduced by an efficient DAP. The DAP feedback can control the acquisition of event waveforms from the large centrally located storage devices holding the raw seismic sensor data for a specified number of hours.

It is anticipated that interactive processing is most applicable to functions performed at the central facility. Other data processing functions, performed at remote stations, are simple enough to be done automatically. At the central facility, the Event Classification Processor (ECP) function and possibly the DAP and SCP function can benefit from an interactive processing system. The actions of each of these functions were shown schematically in the preceding section on Figure II-1 and Table II-1. These are further described and summarized here, as follows:

- DAP - The detection assocation processor operates on detection bulletins which are independently generated by detectors at remote seismic stations. The result of these operations is to initiate requests for seismic data. The seismic data is sampled for a specified time span which must be specified for both short-period and long-period data. This data is sent from the remote stations to the central facility. The data is used to verify and document detected events. It is checked and passed on to the event classification processor.

- ECP - The event classification processor operates on waveforms sent to the central facility in response to DAP initiated waveforms requests. The event classification process describes each event parametrically and classifies those events of sufficient interest to require the study of additional data from the remote stations. A report of the event parameters and the event waveforms is passed on to the system control processor for quality control and subsequently is deposited into a data bank.

- SCP - The system control processor routinely deposits event waveforms and associated descriptor reports into a data bank and, on request, can retrieve these data as required. It also provides system performance evaluation, monitoring of current system status, and updates or brings up routine data processing procedures.

In the following subsections, certain tasks are enumerated. These tasks must be carried out to fulfill the objectives of each function process. The function processes covered are DAP, ECP, and SCP. The

tasks are organized to indicate those which are automatic, provide means for the analyst to observe the results of automatic processing, and provide for the analyst capabilities needed to intervene and influence future data processing.

B. OUTLINE OF DAP TASKS

The primarily automatic tasks performed by the DAP are to:

- Buffer the detection bulletins received from seismic stations.
- Select those bulletins consistent with the estimate of an event location.
- Estimate arrival time at individual stations.
- Initiate entries in a waveform request table.
- For each event, monitor and assign status to the waveform requests.
- For an event, check the quality of all waveforms received. Either retain or re-order waveforms.
- Pass waveforms to ECP.

Computer-DAP analyst linkage is provided by the following optional interrupts:

- Display sequences of station bulletins.
- Display event assocation information, such as the event location, a list of station bulletins associated with the event, and apparent measurement errors.

- Display the waveforms which are available to validate the possible location.

Interactive capabilities obtained by observing the above display follows:

- Control the waiting time and size of buffers for collecting detection bulletins and waveforms.
- Initiate interactive processes to supplement the automatic DAP.
  - Add, delete, or edit the detection bulletins associated with an event.
  - Detect and remove those detection bulletins which are redundant coda detections of large events.
  - Search for and extract later phases of an event.
  - If available, use waveforms to pick more accurate arrival times.
  - Search for and remove bulletins with large timing errors.
- Order waveforms from stations.
- Check the status of communications to and from remote stations.
- Check the quality of waveforms received from stations. Monitor and possibly edit the event parameters which are automatically computed by the DAP.
- Request additional detection data from remote stations to support marginal DAP event detections.

C. OUTLINE OF ECP TASKS

The primarily automatic tasks performed by the ECP are:

- Buffer the waveforms aligned by the expected arrival time of the event.
- Rank order stations by their expected likelihood of detecting the event.
- Filter the waveforms at stations lying within range of the possible event, as indicated by the statistical likelihood of the event amplitude exceeding the noise.
- Detect the event at some of the stations not selected by station detection processors.
- Estimate m_b and M_s from short-period (SP) and long-period (LP) waveforms.
- Detect possible later phases of the event. Collect waveforms to document them.
- Detect P wave first motion. Estimate the arrival time and sign of the first motion.
- Estimate short-period discriminates.
- Compute parameters and tests, which might indicate a possible interfering event.
- Compute statistics needed to classify the event.
- Flag events that need extended processing or extended data acquisition.

- Perform wave analysis of SP and LP waveforms.
  - Group and phase velocity spectrum
  - Amplitude spectrum
  - Focus location and depth estimate
  - Interfering event analysis.
- Prompt the analyst to do interactive processing needed to make difficult event classification decisions.
- Send special requests to stations.
  - Send all sensor data to the central facility
  - Send calibration data to the central facility
  - Act on error flags due to faulty transmissions of data
  - Act on error flags due to possible equipment faults.

Computer-ECP analyst linkage is provided by the following optional interrupts:

- Display the current DAP event list
- Display DAP measurements of event parameters
- Display station recordings (LP or SP)
- Display filtered station recordings
- Display the estimate of the location, location error, and the arrival time anomalies.
- Display measurements of discriminants.

Interactive capabilities based on observing the above displays are:

- Select an event from a list of detected seismic events.

- Examine the event label; accept the event for interactive processing, select another or go back to the automatically controlled mode of ECP processing.
- Select a regional master event to be used to detect LP event waveforms.
- Select a station waveform and filter it to improve the detectability of the event.
- Initialize parameters for filtering.
- Select stations for joint multi-station detection processing.
- Initialize the parameters needed for joint processing.
- Add stations to or delete stations from those used for m_b or M_s estimation.
- Add stations to or delete stations from those used for later phase detection and measurements.
- Add stations to or delete stations from those used for discriminant measurements.
- Edit the data of selected stations, initiate extended processing.
- Classify the event. If it is possibly a explosion, request all sensors and possibly waveforms of extended duration.
- Quality check received waveforms and sensor data. Re-order if necessary.
- Edit the automatically computed event parameters.
- Check the ECP report. Either approve passing control to SCP, reject the event as a false alarm, or hold it for additional processing.

D. OUTLINE OF SCP TASKS

The primarily automatic tasks of SCP are:

- Prepare hourly system status reports
  - File space utilization
  - Queueing lengths
  - Equipment status
  - Alarms set for analyst intervention.
- Manage the disk and operating system to avoid system overloading and to operate with maximum surveillance capacity.
- Enter event parameters and waveforms into a data bank deposit queue.
- Enter requests for event parameters and waveforms into a data bank withdrawal queue.
- Enter programs and parameters for updating the seismic station software into a queue of special messages to the remote stations.
- Enter special requests for quality control data and information.
- Check the execution of general requests. If necessary trouble-shoot failures to execute requests.

Computer-SCP analyst linkage is provided by the following optional interrupts:

- Display hourly system status reports.
- Display DAP or ECP reports.
- Display event waveforms.
- Display tables which are used to control the operating system and to manage the data bases.

- Display sensor data and processed information held at the stations.
- Display reports on the status of communication channels and delayed messages.
- Display reports on the status of equipment.
- Display reports on the system performance.

Interactive capabilities based on observing the above displays are:

- Request time sequences of specified performance parameters.
- Request a simulation of the system to predict possible future overloading or performance degradation.
- Command optional changes in function rules, protocol, or disk allocations to protect system from overloading.
- Check waveforms, analyst transaction reports and data bank transaction reports. Correct errors.
- Check communications status and execution status of queued requests. Adjust thresholds to reduce traffic on overloaded communications channels.
- Order waveform data needed for research and regional corrections updating.
- Order tape buffering or disk switchover to avoid data losses due to system overloading.
- Bring up inoperative systems, initialize operating system tables, and allocate disk storage by file categories.

E. CONCLUSIONS

An interactive processing system provides opportunities for the analyst to examine the status of files generated by automatic processing and to examine the current results of the automatic processing. The analyst then influences the final results by invoking the execution of special purpose programs and optimizing the parameter settings required by those programs. To develop this capability in the easiest possible way, the DAP, ECP, and SCP functions are organized in terms of workload sub-division between automatic data processing, results/display processing, and the analyst's input to influence processing.

SECTION IV

SPECIAL PURPOSE ANALYST INVOKED PROCEDURES

A. INTRODUCTION

In this section certain special purpose procedures will be recommended for interactive processing. It will be apparent to the reader that some of these procedures could be done automatically. The main tradeoff between automatic processing and interactive processing is increased flexibility for an analyst to interpret data and to control machine processing. This increased flexibility is traded for less of the more efficient automatic processing. This tradeoff will continue, as an evolutionary learning process, until the optimal automatic procedures are developed. At that time, the procedure becomes entirely automatic unless analyst interpretation can offer inherently superior capabilities over existing automatic processing algorithms. The examples selected for discussion in this section are those tasks in which a seismic analyst may contribute his capabilities to a normally automatic processing system.

As possible applications for an interactive processing system, certain tasks will be described which are involved in detection association processing (DAP) and event classification processing (ECP). Specific procedures will be described for linking machine processing and analyst interpretation. This linkage is designed to most efficiently and most accurately accomplish the goals of the surveillance system. The interactive processing tasks will usually be initiated by an analyst intervening to check the results

of machine processing. It is also anticipated that special files will be created by automatic processing algorithms. These algorithms will flag ambiguous cases where analyst interaction is required. For example, an automatic algorithm performing event location may flag the possibility of a large timing error. This initiates a diagnostic message to the analyst requesting visual inspection of a record to resolve the problem.

In the next subsection, an overview is given of all data processing functions. In following subsections, some of the DAP and ECP processing tasks are described which utilize an interactive processing system. The ECP tasks considered are depth of focus determination, separation of overlapping events, and on-line event classification procedures.

B. A SYSTEM OVERVIEW OF SEISMIC SURVEILLANCE PROCESSING

For controlling data flow and data reduction at remote seismic stations, the data collection process (DCP) and the station detection process (SDP) are conceived as essentially automatic processes. At the central facility, requests for event waveform data are originated by the detection association process (DAP). The waveforms received are analyzed by the event classification process (ECP), which may request additional seismic data from the stations. The system control process (SCP) controls the quality of processing throughout the entire surveillance system. The ECP and possibly the DAP will require analysts to interact with the automatic processing. The SCP is not yet sufficiently structured to describe tasks requiring an interactive processing system.

Brief descriptions of the input, output, and data processing are shown in Table IV-1 for all of the major functions.

TABLE IV-1

SUMMARY OF FUNCTIONS AND PROCESSING

Functions	From	Input	Processing	Output	To
DCP	Sensors	Sensor data	Gain range Hold on Disk	Core buffered time gate containing all of the sensors	SDP
	DAP	Routine data requests	Estimate event waveform	SP and LP waveform estimate	DAP
	ECP	Extended data requests	Read all Sensors	Desired SP and LP array data	ECP
SDP	DCP	Updated detector time slice of all SP sensors	Detection processing	Detection Bulletin	DAP
DAP	SDP	Detection bulletins	Association-location	Waveform requests	DCP
	DCP	Routine event data	Quality control	Waveforms DAP event bulletin	ECP
ECP	DAP	Waveforms DAP event bulletin	Refined event parameter estimate Start from preliminary event parameter estimate	ECP event bulletin Event waveform estimate Station waveform estimate(s)	Data Bank
	DAP	Waveforms DAP event bulletin	Preliminary classification of waveforms	Request all sensor data	DCP
	DCP	Desired SP and LP Array Data	Extended processing	Extended event report	Data Bank
SCP	All processors	Hourly status (noise, performance, loading, equipment, etc.)	System status parameter generation	System hardware, software or parameter modification	All Processors

To analyze the interactive processing requirements, the functions are broken down into routine automatic processing of algorithms and interactive processing. In some tasks, where routine processing is not involved, the discussion is limited to only the analysis of the interactive part.

C. DAP PROCESSING

The goal of DAP is to operate on detection bulletins in order to locate possible seismic events. One problem is to receive enough bulletins to accurately locate the event. These preliminary locations should be accurate enough to predict P arrival times within about 15 seconds. The amount of waveform data which must be sent from a station to verify the possible events depends on the accuracy of this DAP location. It is anticipated that at least two minutes of waveform data will need to be sent. Another problem is to make the waiting time to collect bulletins as small as possible to avoid mixing in a false alarm or interfering event.

1. Description of Routine DAP Procedures

The routine processing of DAP can be illustrated by briefly describing the implementation of a master detection method. The DAP processor inputs are detection bulletins which contain estimates of arrival time, wave direction, $dT/d\Delta$, and the z-statistics of the detector output. The detector z-statistic is computed by subtracting from the observed estimate of log (A/T) the value expected for noise. This difference is reduced to a standard normal statistic by dividing by the standard deviation of such measurements given noise.

After waiting for a period of time, the buffer will contain a stack of station detection bulletins. A master detection bulletin is selected from the stack by searching for the largest z-statistic. This is the detection bulletin which is least likely due to seismic noise. This bulletin is used to estimate the location of the possible event and its origin time. Based on these estimates and the 99 percent confidence ellipse of the location estimate, a time-ordered search of other bulletins in the stack is carried out. If another bulletin is found whose location estimate lies within the confidence limits of the master location, the second bulletin's information is used to improve the location estimate. The process continues until at least three or four bulletins are associated. If the location estimate confidence limits meet the requirements necessary to request waveforms, then waveform requests are issued to those seismic stations exceeding minimum likelihood requirement of detecting the event. Much of the interactive processing required will involve actions to be taken in marginal cases, where insufficient information exists to request waveforms. Such actions may involve searching time windows for lower threshold detection bulletins.

2. Some Interactive Processing Capabilities to Improve DAP Performance

Interactive procedures can be invoked to improve DAP processing in special cases. The purpose of the intervention is to add interpretation to the results of the machine processed DAP and to guide the processing toward an improved DAP location estimate. It is anticipated that interactive DAP procedures will be used mainly for marginal association decisions involving locations in areas of surveillance interest. The analyst will base his actions on the apparent error between DAP preliminary location and detection bulletin estimate. In some cases, a final decision on

a questionable association may be defered until additional information, possibly from later phase arrivals, is received. Some of the actions initiated by the analyst are as follows:

- Change threshold tests used to select and to reject stations for association. Some of these tests are:
  - The number of stations required to be associated before initiating a waveform request
  - The minimum location errors estimate before initiating a waveform request
  - The confidence limits required to link stations as associated to the master station as a result of intersecting location error ellipses.
- Omit station bulletins with apparently large timing errors to improve the location estimate.
- Invoke association procedures using later phases.
- Add stations with large ray parameter deviations but with apparently small timing errors.
- Hold marginal associations pending additional detection information.
- Request additional detection data from selected stations and within selected time windows.
- Run experimental tests and bring up new standard DAP procedures.
- Update the algorithm and parameters of a standard DAP procedure.

- Change buffer size used to hold association candidates
- Change waiting time to receive delayed transmission of bulletins
- Change the location algorithm
- Change the criteria for removing interfering coda and later phases.

D. DEPTH OF FOCUS ESTIMATION USING pP MEASUREMENT

1. Weaknesses of pP Observations for Focal Depth Estimation

There are several problems in using apparent pP observation on waveforms to obtain refined depth of focus estimates. Some of these problems are:

- The pP phase from a strong, shallow focus event, is not easily seen due to overlapping with the first motion pulse and coda.
- Weaker intermediate and deeper focus pP is separable as a distinguishable pulse, but can be reliably used routinely for depth estimation only with considerable loss of magnitude detection capability.
- Coda fluctuations, radiation patterns, receiver and source site reverberation, multiple paths, and multiple sources introduce ambiguities in the observation of distinguishable pP pulses.
- Spectral or cepstral detection of shallow interfering pP is ambiguous due to random rippling of the coda spectrum, other interference patterns (due to site and source reverberation, multiple paths and multiple sources), and due to lack of a given signal waveform spectrum.

2. Interactive Processing to Detect and Interpret pP Phases

Due to ambiguities and weaknesses of pP observations, the information from these observations would be used generally by the analyst to improve the calculation of focal depth estimates. The following procedures involve analyst interpretation of waveforms and are best accomplished by interactive processing.

- The time windows searched for possible pP observation should be limited by measurements of P arrival times. The time windows should be within the confidence limits of the depth focus computed from those time measurements.
- Before interpreting the P - pP time delays, certain detection criteria should be satisfied. The detection should depend on the number of stations where P - pP time delays are consistently observed, and on the amplitude of pP peaks relative to the amplitude expected for the coda.
- The P - pP time delay measurements which satisfy the specified detection criteria should be used to estimate the depth of focus of the event.
- Some events which possibly have a shallow depth of focus can be subjected to one of the high resolution P - pP time delay measurement techniques which are given as follows:
  - Maximize the resolution of time measurements between P and pP pulses by pulse compression filtering. To design such filters, use the expected P - pP time window as a filter design fitting interval

- If necessary, use well known cepstral analysis techniques
- Use LP surface wave spectral ratios to estimate focal depth as verification of P - pP time delay measurements.

3. Improving Focal Estimation by Detecting and Eliminating Large P Wave Timing Errors

One procedure to eliminate large P wave timing errors is started by selecting a master station to be used for all of the focal estimates. Each other station is considered separately with the master station and tested for consistency with the focal estimate. First, a value for the focal depth is set as a constraint along with upper and lower limits on the origin time. By sequentially increasing the origin time, a track of possible epicenter estimates can be computed. Consistent pairs of stations should intersect at a nearly common epicenter. The analyst will mark such an epicenter with a light pen and remove those other measurements not consistent with the estimate. By raising or lowering the constrained depth, the analyst can observe whether or not the intersections at the preliminary epicenter are more nearly at a common point for the remaining master station - station pairs. By this technique obviously large timing errors are removed as outliers. The remaining stations then can be used for a least squares estimate of the focus.

E. DETECTING MULTIPLE EXPLOSIONS OR HIDDEN EXPLOSIONS

Some of the factors which make any measurements designed to identify interfering seismic events ambiguous are multiple paths, multiple earthquake dislocation, scattering and conversion to P waves near the source, and forward-scattered P wave reverberations along the propagation path. These effects somehow must be distinguished from effects produced by multiple explosions or from those of explosion P waves hidden in the coda of a nearby earthquake. The goal of the analyst is to correctly identify one of those two situations. These two cases will be considered separately.

1. An Explosion Hidden by a Nearby Earthquake

This method of concealing an explosion will require extended analysis of events from seismic regions which are possible explosion test sites. All events from those areas which are above some threshold magnitude will be considered as opportunities to hide clandestine explosions.

The following procedures can be invoked by an analyst for this purpose:

- Visually scan the coda of the earthquake for the emergence of higher frequency pulses possibly due to an explosion source.
- If such high frequency pulses occur at at least three stations, estimate the location and origin time of the possible explosion.
- Invoke a time lapsed power spectra starting at the beginning of the earthquake P wave and moving through the coda. Repeat after inverse filtering the waveform by the earthquake P wave spectra.
- Pick the start time of high frequency spectral peaks occurring in the time lapsed power spectra of the coda. Estimate the location and origin time of the possible hidden explosion by picking such start times at three or more stations.
- Perform multi-station detection by beamforming each frequency component of the time lapsed power spectra, given a grid of possible locations oriented around the earthquake location. Detect significant power peaks corresponding to a position on the grid.

2. Multiple Explosion Sources

Explosion sources can be designed to simulate earthquakes by detonating more than one device using various delays, relative locations, and charge sizes. The discrimination of multiple explosions is complicated by their complexity and by the enhancement of surface waves. Two situations may be encountered in processing multiple explosion waveforms. The focal parameters and charge sizes may be unknown, as in the case of clandestine weapons tests, or may be known, as in the case of peaceful explosions. These two situations are considered separately.

a. Verification of Given Source Parameters

The following interactive processing procedures may be invoked to verify given source parameters.

- Select a nominal earth model and the given source parameters and generate synthetic seismograms. Observe the errors between synthetic and observed data.
- Perturb the nominal earth model and the given source parameters by the Monte Carlo technique. The analyst selects realizations which reduce the observed error and rejects others. The analyst continues the process until he obtains a satisfactory synthetic realization.
- If unexpectedly large pulses are observed, the analyst determines the location and origin time of the corresponding source component. The analyst changes the charge size of the event component until a sufficiently close synthetic realization is obtained.

b. Detection of a Possible Unknown Multiple Explosion

An analysis procedure must be carried out to determine several things. These are to detect possible cases of multiple explosions, to separate the distinct explosion components, to correlate P phases of explosion components from one station to another, and to locate, time, and estimate the yield of each component. Interactive processing techniques to attain these goals may be:

- Invoke algorithms to detect possible multiple explosions for apparently shallow events from certain regions
  - Short-period discriminant analysis
  - Complex cepstral analysis
  - Long-period discriminant analysis, such as LQ/LR ratio.
- To enhance the cepstral analysis use a pulse compression filter designed on the first motion of the waveform. Beamform selected stations to correlate cepstral peaks with occurrences of peak power on a location grid (location of possible sources).
- Given locations and occurrence times of power peaks on the location grid, estimate the waveforms of each source component for analysis of source parameters.

F. ON-LINE EVENT CLASSIFICATION

The purpose of classification for on-line data collection is to assure the availability of sufficient data for extended processing of interesting events. The principle action resulting from a possible explosion classification is to acquire additional data from stations in order to provide sufficient data to thoroughly analyze the event. An ECP analyst's classification of an event as a possible explosion depends on the following chain of conditions:

- The event is located in an area suitable as a potential test site.
- The event is an earthquake sufficiently large to hide a weapons test.
- The event is a known peaceful explosion.
- The event is a possible weapons test.

In the case of events located in areas suitable as a test site, the following discriminant tests can be invoked by the analyst. These are:

- Depth of focus less than a specified depth.
- Short-period discriminant tests.
- Long-period discriminant tests.
- Multiple source or hidden source discriminant tests.

SECTION V

SUMMARY AND CONCLUSIONS

An interactive processing system is most feasible for seismic surveillance data processing at a central facility serving a system headquarters. Conversely, collection of seismic array data and detection of signals can be done entirely by automatic data processing. The functions which could be performed by an interactive processing system at the central facility are:

- Locate the event and obtain event waveforms
- Describe source parameters
- Classify the event and document those events classified as possible explosions
- Deposit or withdraw seismic data from the mass storage of past detected events
- Obtain information on the performance of the system
- Control quality of the automatic processing through the surveillance system.

The feasibility of an interactive processing system for matched filtering of long-period data was demonstrated by Ringdal and Shaub (1974). They showed that successful application of the interactive approach depends critically on the design of suitable software architecture and on the design of the human factors affecting the users of the system. Important features include.

- Flexible interrupt capability
- Convenient record keeping
- Assumed fast recoverability from analyst errors
- The capability for allowing long delays in the analyst's response to permit him to interpret results
- Flexible partitioning between the interactive and fully automatic modes of data processing.

The tradeoff which is made to acquire these capabilities is to give up some of the general purpose computer system's capability of running any conceivable program for the dedicated computer's capability to respond flexibly and rapidly to the analyst's commands. To achieve maximum efficiency, the general purpose system requires specialized computer operators and programmers to intervene between the analyst's need for computed results and the computer's operations on the data. This results in a long turnaround time to accomplish a specific task. The benefits obtained by the interactive system are that processing is limited to only those program modules needed to perform the analyst's highly structured function, and that a command language can rapidly and directly execute any task needed by the analyst. Thus, the development of the interactive processing consists of developing program modules to perform seismic data processing and of developing an operating system controlled by a standard set of analyst commands via a special purpose command language.

One approach followed in developing such a command language was that of Roman (1973). He described a command language called the Numerical Analysis Problem Solving System (NAPSS). Ringdal and Shaub

applied this methodology to seismic data processing and demonstrated its feasibility by designing a command language known as Seismic Analysis Problem Solving System (SAPPS). Their system used a set of commands to branch from one program module execution to another and provide needed analyst interactive program control. It also supported easy and nearly foolproof recovery from errors and comprehensive and convenient record keeping.

By using a command language driven system the analyst's requirements for data processing are fully integrated into the computer operation. This provides the analyst with a tool to control and manipulate data as he sees fit within the context of the system design and purpose. The analyst has the capability of adding new functions and combining existing functions in any sequence with branching capability backed up with coordinated access to large shared mass storage devices. The user of the interactive system will rapidly learn to use the command language as it gives him the capability to:

- Invoke program executions in a language with which he is already familiar.
- Access files of data labeled by familiar names
- Link programming tasks in any desired sequence with branching controlled by logical tests on computed results.
- Obtain fast turnaround of computing necessary to achieve his functional responsibilities.

The interfacing of interactive data processing systems with the overall operation of a seismic surveillance system depends on organizing the data processing workload into a set of command levels. Each command level pertains to the execution of one specific function process

to acquire only that seismic data which is needed. The starting point of the processing is to store seismic sensor measurements. The ending point is to put into mass storage sufficient seismic data to interpret each detected seismic event. Four functions were considered as possible applications of an interactive data processing system. These are, the association of bulletins describing possible seismic events, source description and classification of seismic events by analysis of the event waveforms, the deposit and retrieval of data into mass storage, and quality control of all data processing by the surveillance system. Each of these function processes was organized by outlining the requirements for automatic processing by the displays invoked by the analyst, and by the control procedures invoked by an analyst.

There are certain tasks involving the interpretation of seismic information and data wherein an interactive processing system offers absolute advantages over presently known automatic data processing algorithms. Several examples of this were discussed. One of these is to obtain more accurate timing and focal estimation of events by detecting large timing errors due to false associations. Other options for applying interactive data processing involved interpretation of highly ambiguous seismic data. The purpose of the analyst invoked options was to more accurately locate and classify the seismic event. These options involve invoking well known data processing algorithms by the analyst and displaying various information and data. It would therefore appear that an interactive processing system can be feasibly applied to numerous seismic data processing tasks.

SECTION VI
REFERENCES

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